REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)

2. REPORT DATE
-12/18/97

3. REPORT TYPE AND DATES COVERED
Final Report, March 1995 – October 1997

4. TITLE AND SUBTITLE
Cascading for Large Effective Third Order Nonlinearities

5. FUNDING NUMBERS
DAAH04-95-1-0153

6. AUTHOR(S)
G. Stegeman

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
CREOL (Center for Research in Electro-Optics and Lasers)
University of Central Florida
4000 Central Florida Blvd.
Orlando, FL 32816-2700

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Dr. R. Leheny
3701 North Fairfax Dr., Arlington, VA 22203-1714

Dr. M. Ciftan
U. S. ARO, P.O. Box 12211, Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
ARO 34226.19-PH

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by the documentation.

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

12 a. DISTRIBUTION / AVAILABILITY STATEMENT
no restrictions

12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

The goal was to investigate phenomena associated with the cascading of second order nonlinear optical processes and identify potential applications. Two categories of cascading effects were found: effects due to the periodic power exchange between beams leading to a nonlinear phase shift; and the formation and properties of quadratic spatial solitons. In the first category, high throughput, all-optical switching has been demonstrated in a nonlinear directional coupler, a mode mixer and a Mach-Zehnder interferometer implemented in $LiNbO_3$ channel waveguides. Also, a novel approach to optical diode action based on second harmonic generation in asymmetric structures was demonstrated. In the soliton case, beam steering, all-optical switching, and a new family of quadratic solitons have been demonstrated experimentally in bulk media. Solitons due to down conversion via the seeded parametric instability have been observed and applications to high gain, output limiting devices identified. It has been shown that high intensity beams are unstable in quadratic media and can lead to the generation of single solitons (beam clean-up) and multiple solitons in one and two dimensions. In slab waveguides, quadratic solitons have been generated in $LiNbO_3$ waveguides and their interactions shown to closely resemble those obtained in bulk saturable third order media.

14. SUBJECT TERMS
second harmonic generation, spatial solitons, all-optical switching devices, cascading, all-optical amplifier with saturated output, beam instabilities, optical diode

15. NUMBER OF PAGES
10

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION ON THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)
Prescribed by ANSI Std. 239-18
298-102

19980520 146

Enclosure 1

(1) LIST OF MANUSCRIPTS submitted or published under ARO sponsorship during this reporting period INCLUDING JOURNAL REFERENCES:

(a) Papers

1. G. Assanto, G.I. Stegeman, M. Sheik-Bahae and E. VanStryland, "Coherent Interactions for All-Optical Signal Processing via Quadratic Nonlinearities", IEEE J. Quant. Electron., QE-31:673-81 (1995)
2. L. Torner, C.R. Menyuk, W.E. Torruellas and G.I. Stegeman, "Two Dimensional Soliton-like Waves with Second Order Nonlinearities", Opt. Lett., 20:13-15 (1995).
3. L. Torner, C.R. Menyuk and G.I. Stegeman, "Solitons with Second-Order Nonlinearities", J. Opt. Soc. Am. B, **12**, 889-97 (1995).
4. P. Vidakovic, J. Zyss, D. Kim, W. Torruellas and G.I. Stegeman, "Large Effective $P^{(3)}$ by Cascading $P^{(2)}$ in Crystal Cored Fibers", J. Nonlinear Optics, 9:239-252 (1995).
5. W.E. Torruellas, Z. Wang, D.J. Hagan, E.W. VanStryland, G.I. Stegeman, L. Torner and C.R. Menyuk, "Observation of Two-Dimensional Spatial Solitary Waves in a Quadratic Medium", Phys. Rev. Lett., 74:5036-9 (1995).
6. C.G. Trevino-Palacios, G.I. Stegeman, M.P. DeMichelli, P. Baldi, S. Nouth, D.B. Ostrowsky, D. Delacourt and M. Papuchon, "Intensity Dependent Mode Competition in Second Harmonic Generation in Multimode Waveguides", Appl. Phys. Lett., 67:170-2 (1995).
7. W.E. Torruellas, D.Y. Kim, M. Jaegger, P. Vidakovic and J. Zyss, "Cascading of Second Order Nonlinearities: Concepts, Materials and Devices", ACS tutorial series #601, edited by G.A. Lindsay and K.D. Singer, (American Chemical Society, Washington, 1994), 509-521
8. G.M. Krijnen, W. Torruellas, G.I. Stegeman, H.J.W.M. Hoekstra and P.V. Lambeck, "Nonlinear Phase Shifts by Cascading in the Cerenkov Regime", chapter in Guided-Wave Optoelectronics: Device Characterization, Analysis, and Design, Proceedings of the 4'th WRI International Conference on Guided Wave Optoelectronics, edited by T. Tamir, H. Bertoni and G. Griffel, (Plenum Press, New York, 1995), p381-9
9. G.I. Stegeman, R. Schiek, G. Krijnen, W. Torruellas, M. Sundheimer, E. VanStryland, C. Menyuk, L. Torner and G. Assanto, "Cascading: Modelling a New Route to Large Optical Nonlinearities and All-Optical Devices", chapter in Guided-Wave Optoelectronics: Device Characterization, Analysis, and Design, Proceedings of the 4'th WRI International Conference on Guided Wave Optoelectronics, edited by T. Tamir, H. Bertoni and G. Griffel, (Plenum Press, New York, 1995), 371-9.
10. W.E. Torruellas, Z. Wang, L. Torner and G.I. Stegeman, "Observation of mutual trapping and dragging of two-dimensional spatial solitary waves in a quadratic medium", Opt. Lett., 20:1949-51 (1995)
11. L. Torner, W.E. Torruellas and G.I. Stegeman, "Beam steering by $\chi^{(2)}$ trapping", Opt. Lett., 20:1952-4 (1995).
12. P. Baldi, C.G. Trevino-Palacios, G.I. Stegeman, M.P. DeMichelli, D.B. Ostrowsky, D. Delacourt and M. Papuchon, "Simultaneous generation of red, green and blue light in room temperature periodically poled lithium niobate waveguides using a single source", Electron. Lett., 31:1350-1 (1995).
13. Y. Baek, R. Schiek and G.I. Stegeman, "All-optical response of a hybrid Mach-Zehnder interferometer due to the cascaded nonlinearity", Opt. Lett., 20:2168-70 (1995).
14. D.-M. Baboiu, G.I. Stegeman and L. Torner, "Collision of solitary waves in quadratic media", Opt. Lett., 20:2282-4 (1995).
15. L. Torner, D. Mihalache, D. Mazilu, E.M. Wright and G.I. Stegeman, "Stationary trapping of light beams

in bulk second-order nonlinear media", Opt. Commun., 121:149-155 (1995).

16. W. Torruellas, L. Torner, Z. Wang, D. Hagan, E. Van Stryland, G. Stegeman, "Observation of Two Dimensional Spatial Solitary Waves in a Quadratic Medium", Optics and Photonics News, 6, 23-24 (1995).

17. R. Schiek, Y. Baek and G.I. Stegeman, "One-Dimensional Spatial Solitons Due to Cascaded Second-Order Nonlinearities in Planar Waveguides", Phys. Rev. E, 53:1138-41 (1996)

18. G.I. Stegeman and W.E. Torruellas, "Nonlinear optical materials for information processing and communications", Phil. Transactions of Roy. Soc. London, 354:745-56 (1996)

19. G.I. Stegeman, "Light wave manipulation via $\chi^{(2)}$ in guided wave geometries", Proceedings of ICONO'2, J. Nonlinear Optics, 15:469-76 (1996)

20. W.E. Torruellas, G.I. Stegeman and G. Assanto, "All-optical switching by spatial walk-off compensation and solitary wave locking", Appl. Phys. Lett., 68:1449-51 (1996).

21. G.J.M. Krijnen, W. Torruellas, G. I. Stegeman, P.V. Lambeck and H.J.W.M. Hoekstra, "Optimization of Second Harmonic Generation and Nonlinear Phase-shifts in the Cerenkov Regime", IEEE J. Quant. Electron., 32:729-38 (1996)

22. G.J.M. Krijnen, H.J.W.M. Hoekstra, G.I. Stegeman, and W.E. Torruellas, "New effects in Cerenkov second harmonic generation in the strong conversion limit", Opt. Lett., 21:851-3 (1996)

23. R. Schiek, Y. Baek, G. Krijnen, G.I. Stegeman, I. Baumann and W. Sohler, "All-Optical Switching in Lithium Niobate Directional Couplers with the Cascaded Nonlinearity", Opt. Lett., 21:940-2 (1996)

24. Y. Baek, R. Schiek, G. Krijnen, G.I. Stegeman, I. Baumann and W. Sohler, "All-optical integrated Mach-Zehnder switching in lithium niobate waveguides due to cascaded nonlinearities", Appl. Phys. Lett., 68:2055-7 (1996)

25. Carlos G. Trevino-Palacios, George I. Stegeman and Pascal Baldi, "Spatial Nonreciprocity in Waveguide Second Order Processes", Opt. Lett., 21:1442-4 (1996)

26. G.I. Stegeman, R. Schiek, L. Torner, W. Torruellas, Y. Baek, D. Baboiu, Z. Wang, E. VanStryland, D. Hagan, and G. Assanto, "Cascading: A Promising Approach to Nonlinear Optical Phenomena Revisited", book chapter in "Novel Optical Materials and Applications", edited by I.C. Khoo and F. Simoni, (Wiley Interscience, New York, 1996), pp49-76

27. G.I. Stegeman, D.J. Hagan and L. Torner, "$\chi^{(2)}$ Cascading Phenomena and Their Applications to All-Optical Signal Processing, Mode-Locking, Pulse Compression and Solitons", J. Optical and Quant. Electron., 28:1691-1740 (1996)

28. P. Agin and G.I. Stegeman, "Multisoliton Generation by Laser Modes in a Frequency Doubling Medium", Appl. Phys. Lett., 26:3996-8 (1996)

29. G. Assanto, D.J. Hagan, G.I. Stegeman, W.E. Torruellas and E.W. VanStryland, "Vectorial Quadratic Interactions for All-Optical Signal Processing via Second Harmonic Generation", Optica Applicata, 26:285-91 (1996)

30. R.A. Fuerst, B.L. Lawrence, W.E. Torruellas and G.I. Stegeman, "Beam Transformation Utilizing Spatial Solitons in the Quadratic Nonlinear Medium KTP", Opt. Lett.,22:19-21 (1997)

31. G.I. Stegeman, "$\chi^{(2)}$ Cascading: Nonlinear Phase Shifts", J. European Opt. Soc. , Part A Pure and Applied Optics, 9:139-153 (1997)

32. G.I. Stegeman, "The Growing Family of Spatial Solitons", Optica Applicata, 26:239-248 (1997)

33. R. A. Fuerst, D.-M. Baboiu, B. Lawrence, W. E. Torruellas, G. I. Stegeman, and S. Trillo, "Spatial Modulational Instability and Multisoliton-Like Generation in a Quadratically Nonlinear Optical Medium", Phys. Rev. Lett.,78:2760-3 (1997)

34. Y. Ueno, G.I. Stegeman and K. Tajima, "Large Phase Shifts due to the $\chi^{(2)}$ Cascading Nonlinearity in Large Walk-Off and Loss Regimes in Semiconductors and Other Dispersive Materials", Jap. J. Appl. Phys., 36:L613-5 (1997)
35. K. Gallo, G. Assanto and G.I. Stegeman, "Efficient Wavelength Shifting Over the Erbium Amplifier Bandwidth Via Cascaded Second Order Processes in Lithium Niobate Waveguides", Appl. Phys. Lett., 71:1020-2 (1997).
36. M.T.G. Canva, R.A. Fuerst, D. Baboiu and G.I. Stegeman and G. Assanto, "Quadratic Spatial Soliton Generation By Seeded Down Conversion of a Strong Pump Beam", Opt. Lett., 22:1683-5 (1997)
37. D.M. Baboiu and G.I. Stegeman, "Modulational Instability of a Strip Beam in a Bulk Type I Quadratic Medium", Opt. Lett., in press
38. R.A. Fuerst, M.T.G. Canva, D. Baboiu and G.I. Stegeman, "Properties of Type II Quadratic Solitons Excited by Unbalanced Fundamental Waves", Opt. Lett., 22:1748-50 (1997)
39. Y. Baek, R. Schiek and G.I. Stegeman, Baumann and W.. Sohler, "Interactions Between One-Dimensional Quadratic Solitons",Opt.Lett. 22: 1550-2 (1997)
40. G. Assanto, C. Conti, G. Leo, G.I. Stegeman, W.E. Torruellas and S. Trillo, "Three Wave Simultons: Quasi-Particles in Quadratic Media", J. Nonlinear Optical Physics and Materials, in press
41. G. Assanto and G.I. Stegeman, "Thin Film Devices for All-Optical Switching and Processing via Quadratic Nonlinearities", Thin solid Films, in press
42. R. A. Fuerst, M. T. G. Canva, G. I. Stegeman, G. Leo and G. Assanto "Robust generation, properties and potential applications of quadratic spatial solitons generated by down-conversion of a pump beam", Opt. Quant. Electron., submitted
43. D-M. Baboiu and G. I. Stegeman, "Interaction of Soliton-like Light Beams in Second-Order Nonlinear Materials", Opt. Quant. Electron., submitted

(b) Contributed Conference Presentations

1. "All-optical Hybrid Mach-Zehnder Switch Based on a Cascaded Second-Order Nonlinearity", CLEO'95 (given by Y. Baek), Baltimore, May 1995
2. "High-Contrast All-Optical Switching by Using Cascading in the Cerenkov Regime", CLEO'95 (given by Gijs J.M. Krinjen), Baltimore, May 1995
3. "Cascaded Non-Linearity in Lithium Niobate Waveguides", CLEO'95 (given by Roland Schiek), Baltimore, May 1995
4. "Intensity-Dependent Mode Competition in SHG in Multimode Waveguides", CLEO'95 (given by C.G. Trevino-Palacios), Baltimore, May 1995
5. "2D Solitary Waves in a Quadratic Medium", CLEO'95 (given by William E. Torruellas), Baltimore, May 1995
6. "Spatial Solitons Caused by Cascaded Second-Order Nonlinearity in $LiNbO_3$ Planar Waveguide", CLEO'95 (given by Y. Baek), Baltimore, May 1995
7. "Interaction of Solitons With Second-Order Nonlinearities", CLEO'95 (given by Daniel-Marian Baboiu), Baltimore, May 1995
8. "Two-Dimensional Spatial Solitary Waves in Quadratic Media", European Optical Society Topical Meeting (given by William E. Torruellas), Val Thorens, FRANCE, January 1996.

9. "Nonreciprocity in waveguide second harmonic generation", (given by C.G. Trevino-Palacios), Proceedings QELS'96, p. 75, Anaheim, CA, June 2-7, 1996.
10. "Interaction phenomena in second-order nonlinear materials", (given by D.M. Baboiu), Proceedings QELS'96, p. 76, Anaheim, CA, June 2-7, 1996.
11. "Self-Trapping in Quadratic Media and Instabilities", (given by G.I. Stegeman), Proceedings QELS-96, p. 178, Anaheim, CA, June 2-7, 1996.
12. "Beam clean-up utilizing spatial optical solitary waves in KTP", (given by R.A. Fuerst), Proceedings QELS'96, p. 179, Anaheim, CA, June 2-7, 1996.
13. "All-optical spatial switching of solitary waves in KTP", (given by B. Lawrence), Proceedings CLEO'96, p. 177, Anaheim, CA, June 2-7, 1996.
14. "All-optical integrated Mach-Zehnder switching in lithium niobate waveguides due to cascaded nonlinearities", (Y. Baek), Proceedings CLEO'96, p. 297, Anaheim, CA, June 2-7, 1996.
15. "Light Trapping in Quasi-Phase-Matched Second-Harmonic Generation", (given by L. Torner), Nonlinear Guided Waves and Their Applications, Cambridge, England, 1996 Technical Digest Series Volume 15, p. 65, August 30 - September 1, 1996.
16. "All-optical steering of spatial solitary-waves through cascading in KTP", (given by G. Assanto), Nonlinear Guided Waves and Their Applications, Cambridge, England, 1996 Technical Digest Series Volume 15, p. 151, August 30 - September 1, 1996.
17. "All-optical switching in integrated directional couplers and Mach Zehnder interferometers with cascading", (given by R. Schiek), Nonlinear Guided Waves and Their Applications, Cambridge, England, 1996 Technical Digest Series Volume 15, p. 249, August 30 - September 1, 1996.
18. "Broadband wavelength multiplexer around 1.55 μm via quadratic cascading in a Lithium Niobate waveguide", (given by G. Assanto), Photonics in Switching & 8th European Conference on Integrated Optics (ECIO'97), April 2-4, 1997, Royal Institute of Technology, Stockholm, Sweden.
19. "Modulational instability of a strip input beam and multisoliton generation in a bulk quadratic equation", (given by D.-M. Baboiu), Proceedings QELS?97, p. 151, Baltimore, MA, May 18-23, 1997.
20. "Interaction of one-dimensional quadratic solitons in lithium niobate planar waveguides", (given by Y. Baek), Proceedings QELS'97, p. 151, Baltimore, MA, May 18-23, 1997.
21. "Large phase shifts resulting from the $P^{(2)}$ cascading nonlinearity in large walk-off regimes in semiconductors and other dispersive materials", (given by Y. Ueno), Proceedings QELS'97, p. 153, Baltimore, MA, May 18-23, 1997.
22. "Generation of two-dimensional spatial soliton patterns by laser modes in a quadratic medium", (given by P. Agin), Proceedings QELS'97, p. 153, Baltimore, MA, May 18-23, 1997.
23. "Observation of modulational instability in a quadratically nonlinear optical medium in one and two dimensions", (given by R.A. Fuerst), Proceedings QELS'97, p. 155, Baltimore, MA, May 18-23, 1997.

(c) Invited Conference Presentations

1. "Progress in Quadratic Solitons", (given by Stegeman), Annual OSA Meeting, October 1997
2. "Experiments with Quadratic Solitons", 3 lectures, (given by Stegeman), NATO Summer School on $\chi^{(2)}$, Sozopol (Bulgaria), September 1997
3. "Cascaded Nonlinear Optics", (given by Stegeman), Gordon Conference on Nonlinear Optics, Tilton

Academy, July, 1997

4. "Cascaded Nonlinear Optics", (given by Stegeman), Pusan National University, Pusan Korea, July 1997

5. "Experimental Realizations of Spatial Solitons", (given by Stegeman), Summer School on Solitons : Concepts And Recent Developments, University de Bourgogne, Dijon, France; ESERG-LEMO University of Grenoble, Grenoble, France; Laboratoire d'Optique des Surfaces et des Couches Minces, University of Marseilles, Marseilles, France, June 1997

6. "Three-wave simultons:quasi particles in quadratic media", (given by G. Assanto), Conferences on Advances in Nonlinear Optics, Cetraro Italy, June 1997.

7. "Second Harmonic Generation, A New Look at an Old Effect", seminar, (given by Stegeman), University of Indiana in Bloomington, December 4, 1996

8. "Cascading Nonlinear Optics", seminar, (given by Stegeman), Bell Labs, November 1996.

9. "Applications of Cascading Nonlinear Optics", (given by Stegeman), Annual LEOS'96 Meeting, Boston, November 1996

10. "Spatial Solitary Waves Using Second Order Nonlinearities", (given by B. Lawrence), Annual LEOS'96 Meeting, Boston, November 1996

11. "Cascading Spatial Soliton Phenomena", (given by Torruellas) Annual ILS/OSA Meeting, Rochester NY, October 1996

12. "Cascaded Optical Nonlinearities in Organic Structures", (given by Torruellas), IQEC'96, Sydney, Australia, July 1996

13. "Experimental Progress in Cascading Nonlinear Optics", (given by Stegeman), Nonlinear Optics: Phenomena and Applications, Maui, July 1996

14. "Trapping of Light Beams and Formation of Spatial Solitary Waves in Quadratic Nonlinear Media", (given by Lluis Torner), QELS'96, Anaheim, June 1996

15. "Cascading $\chi^{(2)}$ Processes", (given by Stegeman), Workshop on $\chi^{(2)}$ Second Order Nonlinear Optics: From Fundamentals to Applications, Les Houches France, April 1996

16. "All-Optical Materials and Their Applications to Communications", (given by Stegeman), CRL International Symposium on Advanced Technologies in Optical communication and Sensing", Tokyo, March 1996

17. "Observation of Two Dimensional Spatial Solitary Waves in a $\chi^{(2)}$ Medium", (given by W. Torruellas), IEEE LEOS Annual Meeting, San Francisco, October 1995

18. "Cascaded $\chi^{(2)}$ Nonlinearities", QE-12, (given by Stegeman), Southampton, September 1995

19. "Cascaded Nonlinearity in $LiNbO_3$ Waveguides", CLEO'95 (given by R. Schiek), Baltimore, May 1995

20. "Two Dimensional Solitary Waves in a Quadratic Medium: The Experiment", QELS'95 (upgraded, given by W.E. Torruellas), Baltimore, May 1995

21. "Cascading of 2nd Order Nonlinear Processes", (given by Stegeman), European Conference on Integrated Optics, Delft Holland, April 1995

22. "Nonlinear Optical Materials for Information Processing", (given by Stegeman), Royal Society Meeting on "Nonlinear Optics for Information Processing", London, March 1995

(2) SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

Faculty: G.I. Stegeman; *Postdoctoral Fellows:* W. Torruellas, M.Canva; *Graduate Students:* Y. Baek, B. Lawrence, C. Trevino-Palacios, Russell Fuerst, Daniel Baboiu
PhDs Awarded: Yongsoon Baek, "Cascaded Second Order Nonlinearities in Lithium Niobate Waveguides", PhD Thesis, Summer semester 1997, completed.

(3) REPORT OF INVENTIONS (BY TITLE ONLY):

(4) SCIENTIFIC PROGRESS AND ACCOMPLISHMENTS - Describe research Progress and accomplishments, including significant theoretical or experimental advances.

ACOMPLISHMENTS:

The research achievements covered here are for the duration of the award.

The goal was to investigate the physics and applications of "cascading" effects which involve periodic power and phase exchange with distance between beams interacting via second order nonlinearities. Specifically, when a beam of frequency ω traverses a nonlinear (second order) material, both its amplitude and phase are modified in a power-dependent way (and some second harmonic is generated [SHG]). The effects we explored can be separated into effects connected primarily with the *nonlinear phase shift,* and the *nonlinearly modified amplitude which leads to spatial solitary waves.*

Nonlinear Phase Shift Phenomena:

(a) We had previously shown that large nonlinear phase shifts could be achieved with at most 10% fundamental loss to SHG in $LiNbO_3$ channel waveguides using mode conversion $[TE_{00}(\omega)\rightarrow TM_{00}(2\omega)]$ for phase-matching at 360^0C at 1320 nm. The key was that the temperature profile of the oven and hence the wavevector mismatch with position was not uniform in a special way. We have now used this phenomenon to demonstrate all-optical switching in a nonlinear directional coupler, nonlinear mode mixer and a nonlinear Mach-Zehder for the first time. This is a significant achievement because (i) these are very sophisticated switching devices known, and (ii) because in the case of the nonlinear directional coupler, it has two input and two output ports, allowing a large variety of all-optical operations. All-optical switching was observed based on cascading with a contrast ratio approaching 5:1 and 80% throughput. *It is now clear that any all-optical device may be implemented with cascading nonlinearities.*

(b) The application of cascading to frequency shifting of 1.55 μm signals for wavelength division multiplexed (WDM) systems in the erbium amplifier wavelength window. The concept is as follows: first a pump signal (ω_p) in the erbium amplifier window is doubled. In the same waveguide, the doubled signal then acts as the pump for difference frequency mixing with an input signal ($\omega_i = \omega_p \pm \Delta\omega$) in the erbium window which produces an output signal at $\omega_o=\omega_p \mp \Delta\omega$. By choosing ω_p appropriately, frequency shifting anywhere within the erbium amplifier window can be implemented. Calculations show that the 3 dB bandwidth of this caascading process covers the full erbium spectral window (±40nm) and frequency shifted signals down by 10 dB from the input signal are feasible with pump laser powers of a few hundred milliwatts in QPM $LiNbO_3$ channel waveguides. The signals have just been observed in a crude experiment utilizing an erbium fiber laser (input signal) and a color center laser (pump). *The advantage of this WDM frequency shifting scheme is that only lasers operating in the* *communications band are used, there is no mode-matching requirement which occurs when only difference frequency mixing is used (by other researchers), the doubled frequency signal can be eliminated in a novel double pass geometry and that the power requirements can be met with existing semiconductor or fiber lasers.*

(c) We also investigated QPM channel waveguides at 1600 nm in collaboration with Dan Ostrowsky's group in Nice. The waveguides which are single mode at 1600 nm can support a number of modes at the harmonic. We found that the nonlinear phase shift produced for one of the harmonic modes which was near its phase-matching condition could detune another harmonic mode, phase-matched at low input powers, away from its phase matching for increasing input power. That is, the two modes would compete for the fundamental power as the input power was increased. *The resulting mutual detuning led to an apparent saturation of the SHG process, and may be the origin of the apparent "saturation of SHG" reported by many authors in waveguides.*

(d) Also in the "Nice" QPM waveguides we have observed a very interesting, initially unexpected effect which has been identified as spatial non-reciprocity in non-centrosymmetric media. By coating photoresist onto a channel waveguide over part of its length, we found that the second harmonic conversion efficiency depended upon which end of the waveguide was used as the input, the overcoated end or the uncoated end. Prior to the film deposition the SHG did not depend on the input direction. We now understand this effect as being due to a phase-mismatch for SHG which is not symmetrical about the middle of the sample. The conditions for "seeding" the SHG process when entering from coated to uncoated regions, and vice versa, is different for the two cases and hence the final SHG output is different. Modeling confirmed the observed effect and its origin. *This phenomenon could find application to an optical diode.*

Spatial Quadratic Soliton Phenomena:

We had previously reported the observation of strongly coupled fundamental and harmonic beams which propagate without spatial diffraction in two dimensions, i.e. in bulk second order media. This is completely new physics which we have been exploring both theoretically and experimentally in one (slab waveguides) and two dimensions (bulk crystals).

(e) The process by which quadratic solitons are generated in bulk media, solitary-wave locking, can be used to change and control the propagation direction of beams inside a SHG-active crystal for which one or more of the interacting beams experiences walk-off at low powers. We demonstrated this effect previously by using a seed second harmonic with a specific phase. We have now verified experimentally that the same effect can be implemented in Type II SHG by tuning the relative intensity of the two input fundamental beams. This is important because the relative phase of the two inputs is irrelevant and hence the process is phase-independent. By varying the relative intensity the direction of the beam can be tuned smoothly from one direction to another. By placing apertures at the two directions, all-optical switching was observed with less than a 10% change in the input intensity. *This constitutes a totally different approach to all-optical switching, logic etc.*

(f) A new family of bulk quadratic solitons has been discovered in Type II phase-matched interactions. Solitons with different ratios (from those obtained in SHG) of the second harmonic, the o-polarized fundamental and the e-polarized fundamental were observed. In fact, these ratios can be tuned continuously by changing the input polarization. *The key result is that a quadratic soliton can be launched with primarily one fundamental polarization.* This means that a soliton can be formed with a strong pump beam and a weak signal beam, and that the weak signal beam can be guided by the strong pump beam as a quadratic soliton. The direction of the strong pump can in principle be controlled electro-optically because the materials which support quadratic solitons are also electro-optic active. *This has applications to reconfigurable interconnects.*

(g) These bulk quadratic solitons have many properties in common with the well-understood spatial solitons based on Kerr third order nonlinearities. One of these is the "robustness" of the solitary waves. Thus input beams of sufficient intensity will evolve adiabatically with distance into spatial solitary waves. The preliminary observation was introduced in the 1995 report. This effect has now been explored thoroughly and then "verified" by beam propagation calculations. Experimentally, elliptical beams with different major:minor axes ratios, up to 12:1, were launched into the doubling crystal KTP. We have now extended our previously reported preliminary results to show that in each case the output was transformed into a perfectly cylindrically symmetric output beam. The threshold values versus ellipticity have been measured and good agreement with theory found. *This effect can be used to transform spatially noisy (spikes) or irregularly shaped outputs (for example, from linear semiconductor arrays) into circular beams.*

(h) An intriguing effect was reported previously in which the input intensity of the elliptical beam was high. The beam "broke up" into a line of cylindrically-shaped solitary waves. Up to 10 have now been observed. This effect has now been studied extensively and found to be a result of modulational instabilities in one dimension (along the major axis of the ellipse) of a beam in a quadratically nonlinear medium. Excellent agreement with a new theory was obtained. That beams break up in self-focusing media due to third order nonlinearities is well-known from the early days of nonlinear optics. This is the first observation of beam break-up in media used for SHG, tunable parametric generation devices (OPOs, OPGs etc.) and places limitations on such devices. In fact, it is highly likely that the beam filamentation and resulting damage observed in quadratically nonlinear media is due to cascading effects and not self- focusing due to third order nonlinearities. For very high intensities, break-up in the second dimension (along the minor ellipse axis) was also observed. *These phenomena can be used to better design high power devices in quadratic media and to generate soliton patterns in one and two dimensions.*

(i) Quadratic soliton formation during parametric down-conversion has been discovered and a fascinating device possibility uncovered. A pump beam (at 2ω) and a weak seed (at ω) have been observed to generate a quadratic soliton for Type II phase-matching. This corresponds to the degeneracy point of an OPO. Because of the well-known parametric instability, a photon from the pump beam breaks up into two fundamental photons via an exponential growth process. This process is controlled and limited by the formation of a quadratic soliton. For a given pump beam input, the output is clamped at a well-defined quadratic soliton, independent of *the fundamentals amplitude, phase and polarization.* Furthermore, the process has been verified to be only weakly dependent on beam overlap in space and time, in keeping with the its "seed" nature. *This all-optical process provides up to 40 dB gain for the weak fundamental, and also clamps it's output at a fixed value (determined by the "power supply", i.e. the harmonic intensity: These characteristics are that of a robust amplifier-limiter device.*

(j) One dimensional quadratic solitary waves have been observed in $LiNbO_3$ slab waveguides based on Type I phase-matched SHG. When a fundamental beam (at 1320 nm) was launched into the slab waveguide, a 1D quadratic soliton was formed and appeared at the output. Solitons were observed both near and far from phase-matching and the results were in excellent agreement with theory. *This should make possible most of the phenomena that we observed in the 2D case, but with much lower power requirements.*

(k) The interaction between two 1D solitons launched in both a parallel and a crossing geometry has been investigated experimentally and numerically. The result of the interaction depends on the relative phase between the two launched fundamental beams. For parallel launching and phase angles of 0 and π, the solitons fuse and repel one another respectively. At π/2 and 3π/2, the beams exchange power before separating. For crossing geometries, the behaviour was essentially the same for small incidence angles. However at larger angles, no fusion occurs but the attractive and repulsive forces for phase angles of 0 and π lead to different lateral deflections of the output solitons. Furthermore the power exchange at other angles is reduced. *This phenomenon has applications to beam combining and sets limitations on soliton crossing angles for applications such as optical interconnects.*

(5) TECHNOLOGY TRANSFER - Describe any specific interactions or developments which would constitute technology transfer of the research results. Examples include patents, initiation of a start-up company based on research results, interactions with industry/Army R&D Laboratories or transfer of information which might impact the development of products.

"Applications of Solitary-Wave Locking in Second Order Parametric Processes", awarded